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Laser-Doppler Blood-Flowmetery Modeling by Monte Carlo Method

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Abstract **- Laser Doppler Flowmetery (LDF) is a noninvasive method to assess tissue blood flow. Previously published works have proposed a mathematical model for LDF and showed that there is a relationship between first moment of power spectrum and the velocity of moving blood cells (MBC's). Also researchers have studied this method by mathematical analyses in various aspects. In this paper a new model for LDF based on Monte Carlo method is proposed. We have shown that this new model is more flexible and provides a better agreement with the experimental results. For example this model represents the nonlinear relationship between the first moment of power spectrum and the blood cells velocity which is not seen in previous models.**

Index Terms **- Laser Doppler, Blood Flowmetery, Monte Carlo Method**

I. Introduction

Laser Doppler flowmetery (LDF) is a noninvasive technique for measuring blood flow in tissue. In this method a coherent laser light illuminates the tissue and the scattered light from skin surface which part of that is Doppler shifted is collecting by the photocurrent.

A mathematical model for LDF has been proposed by Bonner and Nossal [1]. Due to high scattering properties and complex structure of tissue, this model presumes a uniform light around any blood cell. Under normal conditions a backscattered photon usually coincides with more than one MBC that is called "multiple scattering" effect. By considering the Poison distribution function for number of coincidence of a photon with MBC's, this effect is also taken into account. Bonner and Nossal showed that the first moment of photocurrent power spectrum $\langle\omega\rangle$ is proportional to root mean square of blood cells velocities $\langle v^2\rangle^{1/2}$ [1]:

$$\langle\omega\rangle = \frac{\langle v^2\rangle^{\frac{1}{2}}\beta}{(12\xi)^{\frac{1}{2}}a} f(\bar{m}) \qquad (1)$$

where v is blood cells velocities, β is an instrumental factor, ξ is a factor related to shape of cells, a is the radius of an average spherical scatterer and $\bar{m}$ is mean number of coincidence of a photon with moving cells that is proportional to concentration of MBC's. For $\bar{m} << 1$ the $f(\bar{m})$ function is linear.

Experimental results achieved by Ahn et al. [2] show that for low values of blood cells velocities (<100 ml.min^{-1}.100g tissue) there is a linear relation between blood cells velocity and first moment of power spectrum. But for higher values of blood cells velocities this relation becomes nonlinear.

In this paper a new model is proposed for LDF measuring of blood perfusion at skin. It is based on Monte Carlo method and simulation of photons transmission through the tissue. Doppler effect is also considered in this model. The computer simulation showed a nonlinear relationship similar to the experimental findings. The Monte Carlo method ability to obtain and presume a wide range of parameters make this method a good approach to study the LDF method for measuring skin blood flow.

II. The Model

A layered model is considered for the skin. Such a model has been used by other researchers and has considerable accordance to experimental results [3, 4]. Photons are considered in groups named *packet*. This decreases the deviation of results and lets considering variable weights for packets. To perform the Monte Carlo method, N photon packets are considered with initial weight w_0=1 (which will be normalized during the process). Movements of each photon is simulated from initial position until it exists from skin surface or its weight yields negligible effect on final results. Every photon may experience the scattering, absorption, refraction, reflection or Doppler effect during the propagation through the tissue. To simulate these phenomena the following parameters should be known for the desired laser wavelength. These are layer refraction index n, absorption coefficient μ_a, scattering coefficient μ_s, mean-cosine of scattering angle g, and layer thickness d. For biological tissue the Henyey-Greenstein distribution function for cosine scattering angle distribution function shows acceptable agreement to experimental results [3]. This function is defined as [6]:

$$p(\cos(\theta)) = \frac{1-g^2}{2(1+g^2-2g\cos\theta)^{\frac{3}{2}}} \qquad (2)$$

In each step a photon passes the free length s and comes to interaction site. Free length is calculated as [7]:

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Abstract

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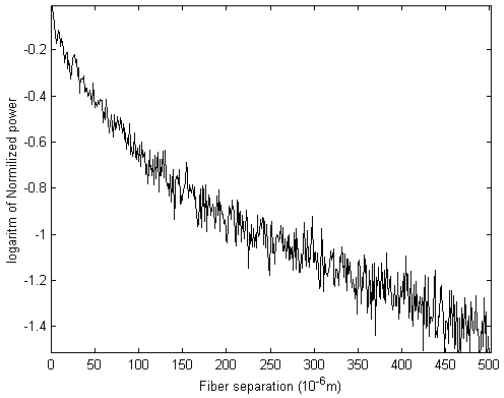

Figure 1. Logarithm of normalized power against fiber separation.

$$s = -\frac{\ln(\xi)}{\mu_a + \mu_s} \qquad (3)$$

where ξ is a random value between 0 and 1 with uniform distribution function. Interaction point is the site where a photon is absorbed and scattered.

Red blood cells provide dominant number of erythrocytes in blood. Also blood plasma makes low scattering and is much more transparent than red blood cells. Therefor it can be assumed that every interaction point in the blood layer is a blood cell. Doppler shift can be calculated as [8]

$$\Delta f = \left(\vec{K}_s - \vec{K}_i\right).\frac{\vec{V}}{2\pi} \qquad (4)$$

where Δf is Doppler shift, $\vec{K}_s$ is scattered vector, $\vec{K}_i$ is incident vector and $\vec{V}$ is velocity vector. Scattering and incident vectors are known for every photon at interaction point during simulation and Doppler shift can be calculated. These shifts are added together for every photon

III. Results

A five-layer structure is considered for skin. Optical parameters are shown in table 1 for He-Ne Laser wavelength (633 nm) that is widely used for LDF measurements. Laser beam radius is considered 0.1 mm. Power reduction of

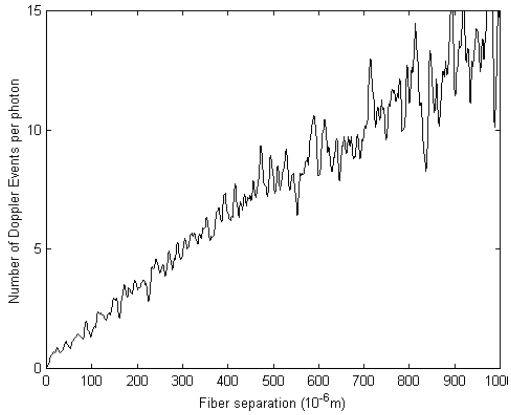

Figure 3. Mean number of Doppler events per photon against fiber separation.

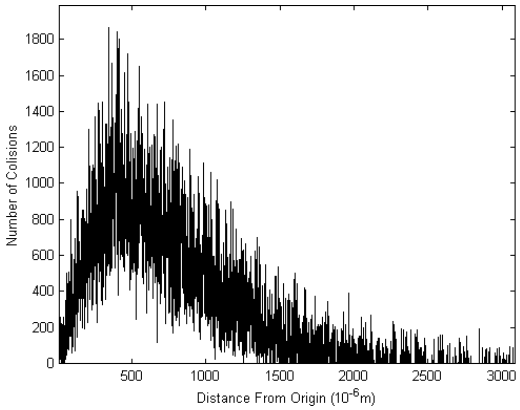

Figure 2. Total number of photons collisions with moving blood cells against distance from incident laser beam origin.

photons relative to distance from the laser source have a shape roughly close to an exponential function (figure 1) as have been obtained by computational calculations [7] and experimental results [8]. Mean number of photon collisions with MBC's increases linearly relative to distance from laser beam origin (Figure 2) as obtained by computational calculation [9], mathematical model and experimental results [10].

Total backscattered power from tissue is 22% of power diffused in tissue. 0.78% of the total backscattered power is obtained from photons that make the Doppler signal. Photons that have diffused only in epidermis layer make 56% of the total power received at the skin surface. This means that epidermis layer has dominant absorption of laser power. The model shows that the maximum value of $\overline{m}$ occurs in about 0.5 mm distance from laser beam origin (Figure 3) which means that this fiber separation is optimum to have maximum signal to noise ratio. It has good agreement to LDF instruments that use a value between 0.5-1 mm [11].

First moment of Doppler frequency power spectrum has obtained for different velocities. A gaussian distribution function is considered for photons velocities. Figure 4 shows the power spectrum of backscattered photons from skin surface for different values of cells mean velocities. Figure 5 shows first moment of photocurrent power spectrum relative to mean velocity of blood cells. As it can be seen, for lower

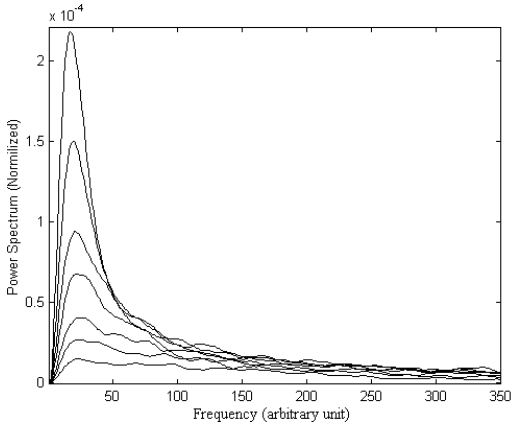

Figure 4. Power spectrum of photocurrent for different velocities of moving cells smoothed by a second order butterworth filter.

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Table 1. Skin parameters for 633 nm wavelength at various layers [5].

Layer	d μm	g	n	μ_s $(\mu m)^{-1}$	μ_a $(\mu m)^{-1}$
Epidermis	65	0.79	1.55	0.048	0.0035
Upper Dermis	350	0.82	1.55	0.0187	0.00027
Blood Layer	100	0.98	1.33	0.04	0.0025
Lower Dermis	550	0.82	1.55	0.0187	0.00027
Subcutaneous fat	320	0.8	1.45	0.002	0.00002

values of cell velocities the relation is near to linear. By increasing the blood cells velocities a reduction occurs in first moment of power spectrum. This model shows a well accordance to experimental results

IV. Conclusions

The Monte Carlo model proposed in this paper for LDF of skin has shown to be a viable tool for study of blood perfusion of skin. The simulation results have shown to be in good agreement to experimental results. The Doppler effect is considered in this model. The nonlinear relation between first moment of power spectrum of photocurrent and blood velocity was presented in the results. Wide range of Monte Carlo method parameters can lead the model for a more accurate simulation.

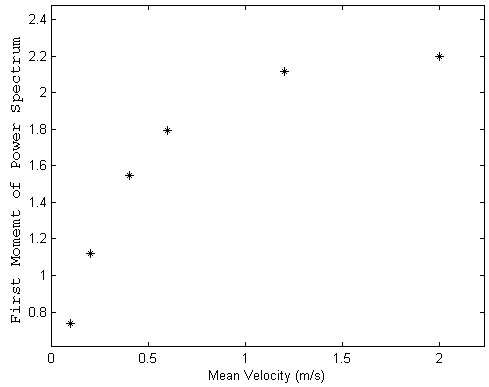

Figure 5. First Moment of power spectrum relative to mean velocity of moving cells.

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